4 Star Formation Relations

(+ Strengthened Cluster Survival)

With One Single Model

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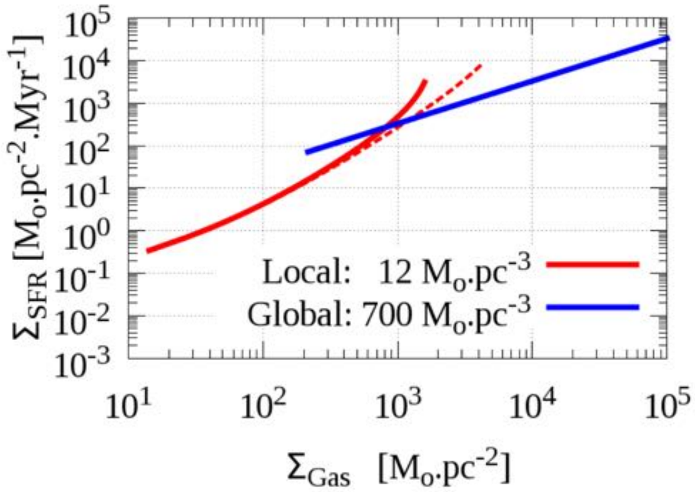
Outline

Star cluster formation in centrally-concentrated molecular clumps

A. Gas-embedded systems

➤ **What star formation relations characterize such systems?**



Outline

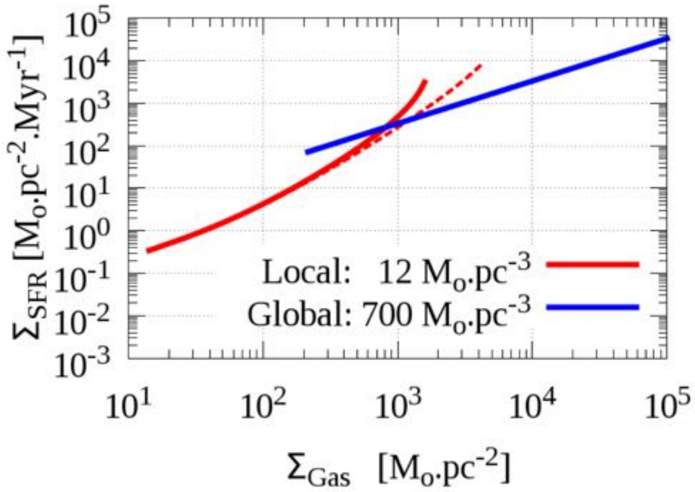
Star cluster formation
in centrally-concentrated
molecular clumps

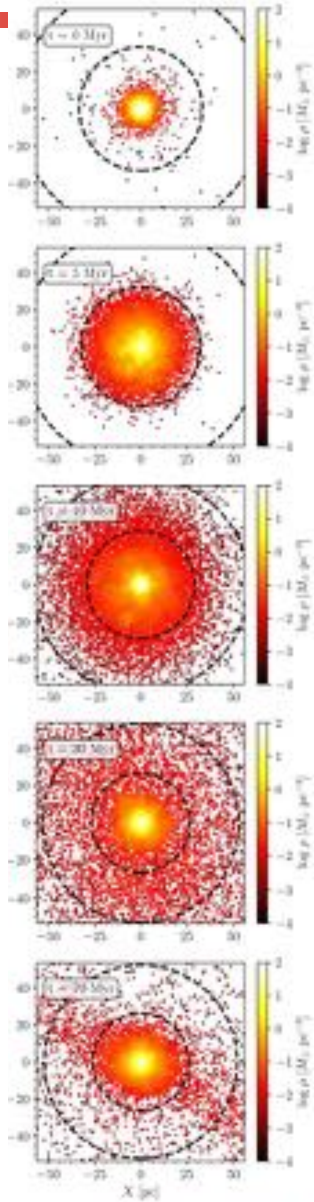
B. Gas-free systems

➤ When the residual star-forming gas is gone, how do such systems evolve ?

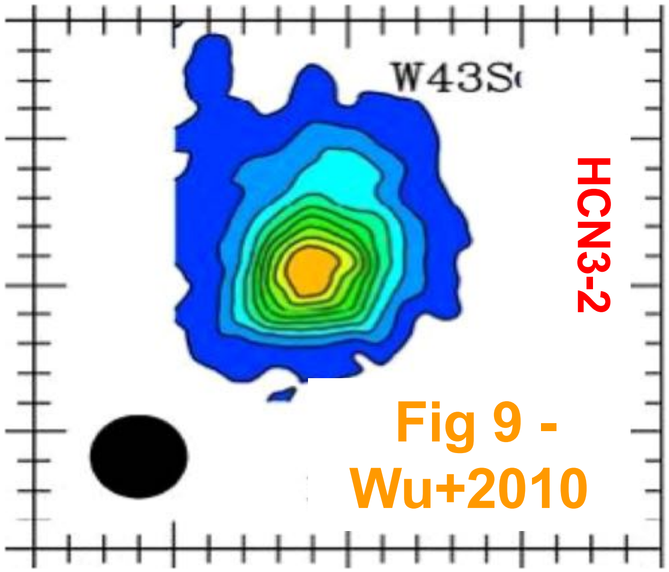
A. Gas-embedded systems

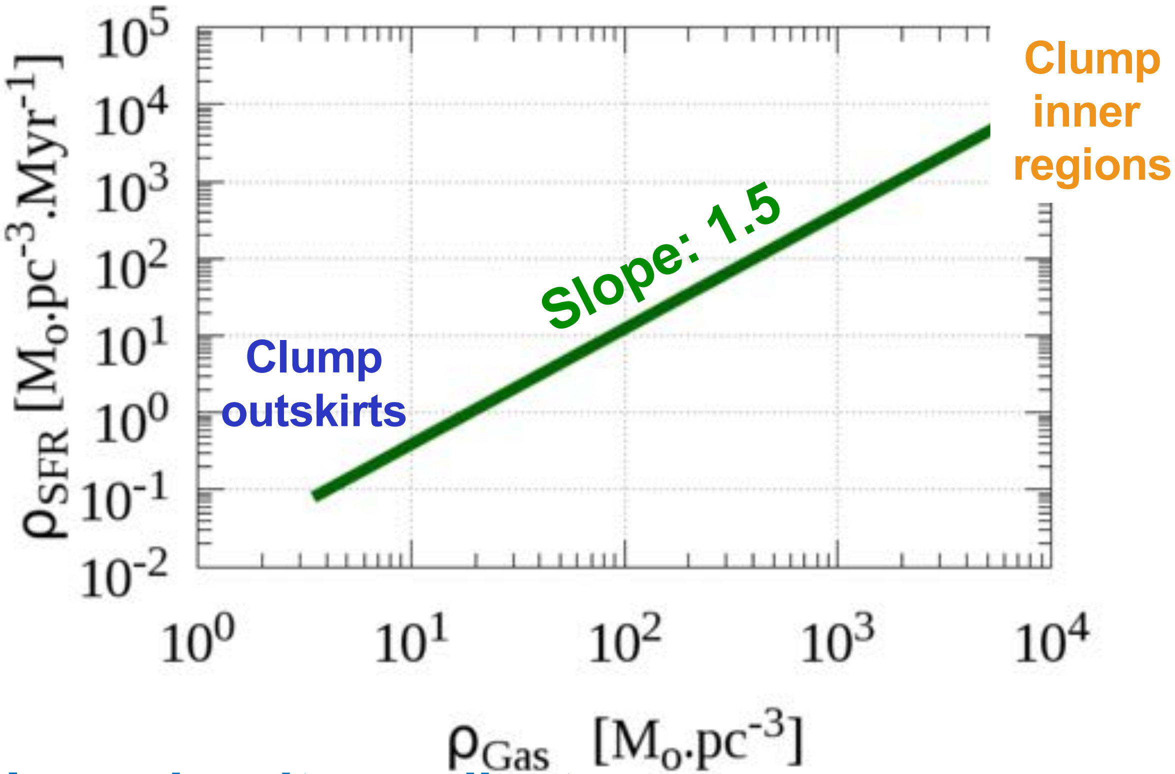
➤ What star formation relations characterize such systems?





First Star Formation Relation (Volume/Theory)



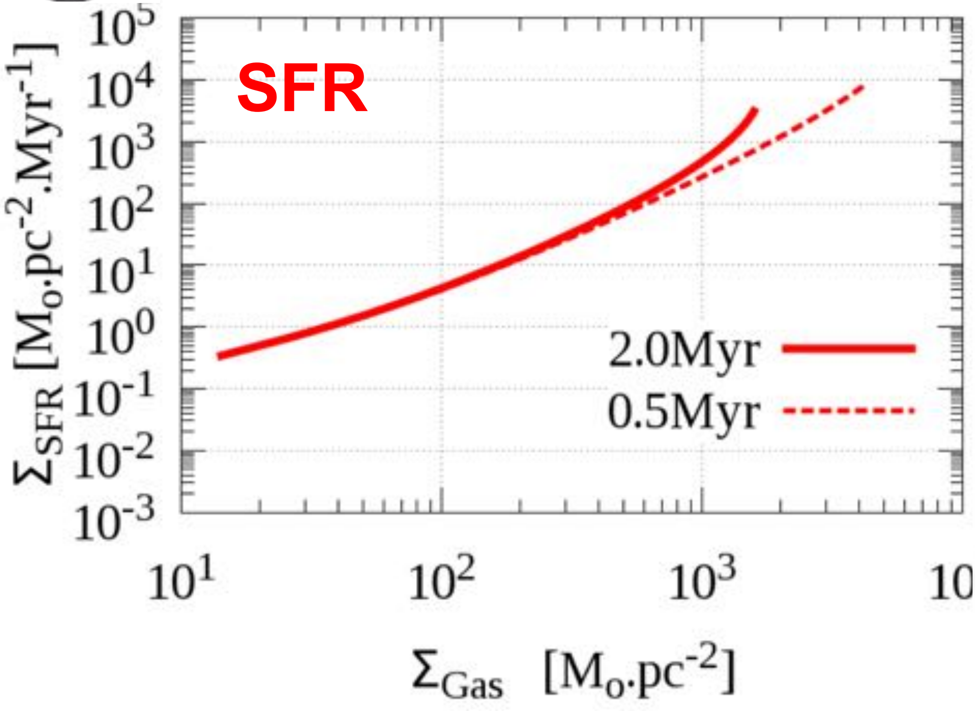


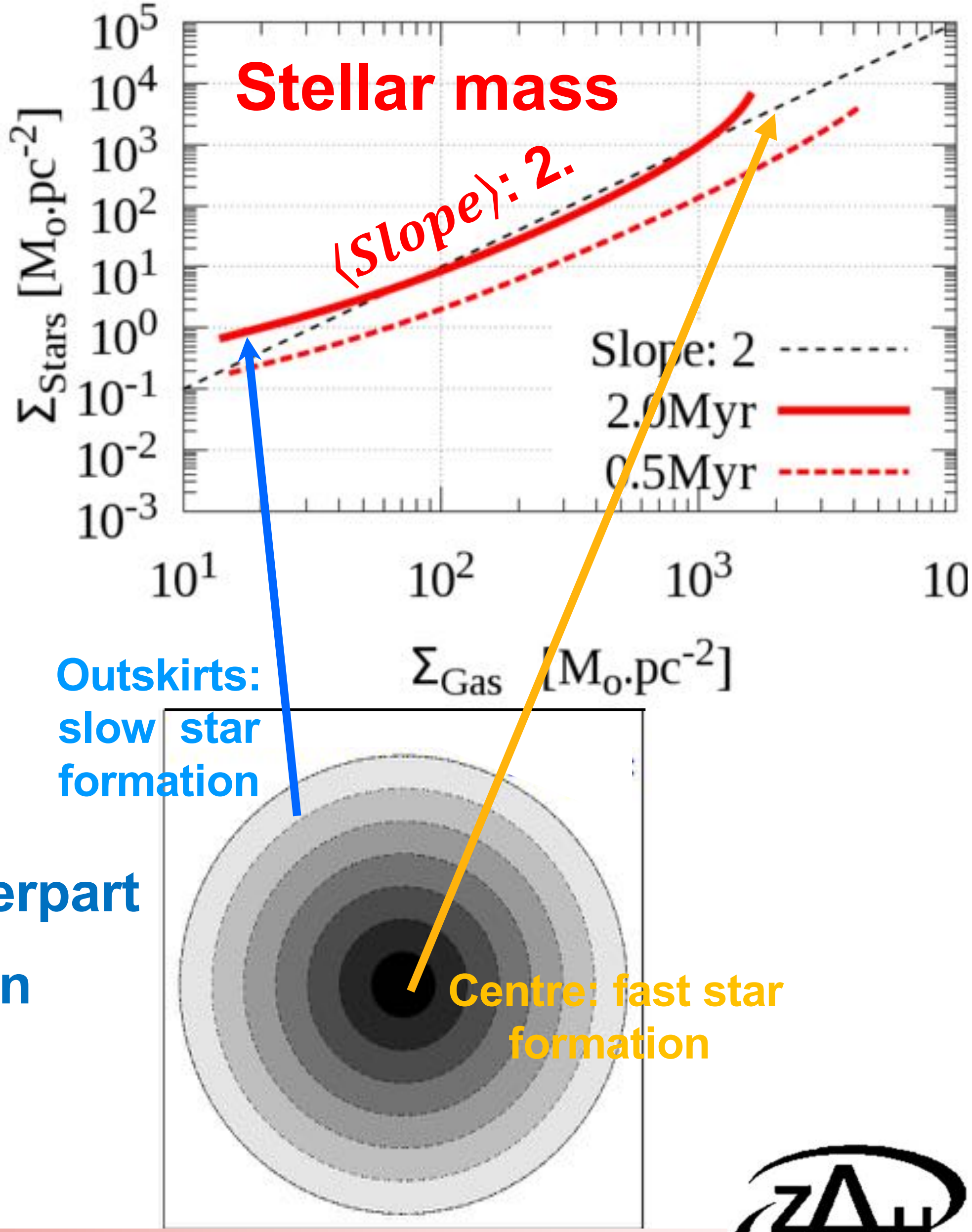
- Molecular clumps have volume density gradients
- If stars form with a constant star formation efficiency per free-fall time, ε_{ff}, the volumetric star formation relation is a power-law of slope 3/2
- Shell-by-shell representation
- Local star formation relation

$$\rho_{SFR} = \frac{\varepsilon_{ff}\,\rho_{gas}}{\tau_{ff}}$$

I. $\rho_{SFR} \propto \rho_{gas}^{1.5}$

Second Star Formation Relation (Surface/Observ.)





II. $\Sigma_{SFR} \propto \Sigma_{gas}^{2}$

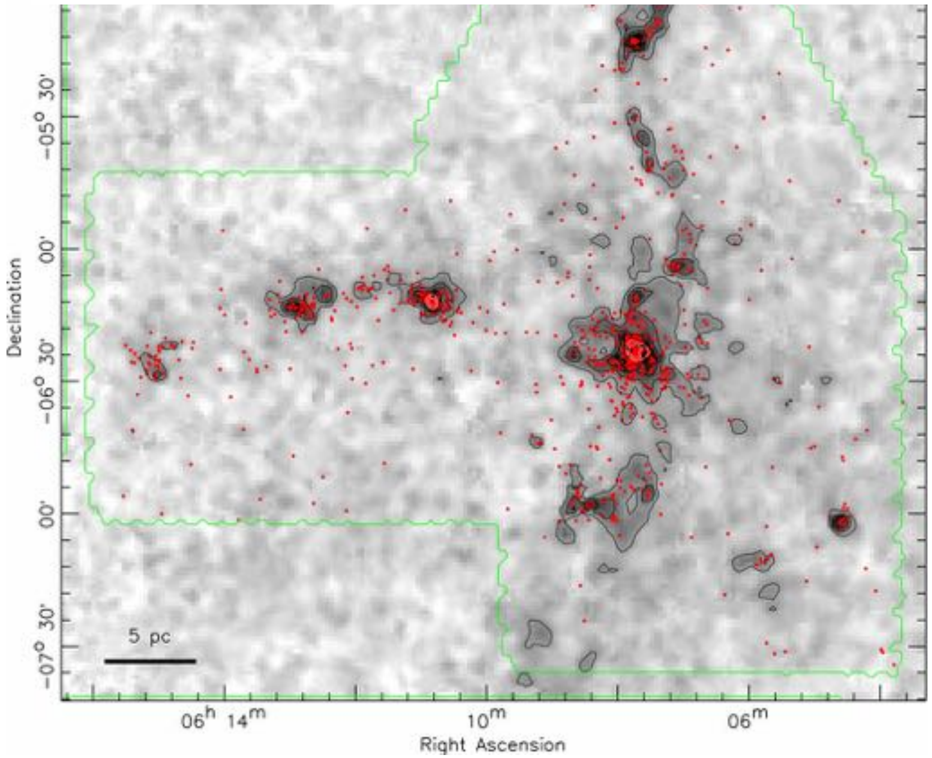
- Steeper than its volumetric counterpart
- Contour-by-contour representation
- Local star formation relation

Parmentier & Pfalzner (2013)

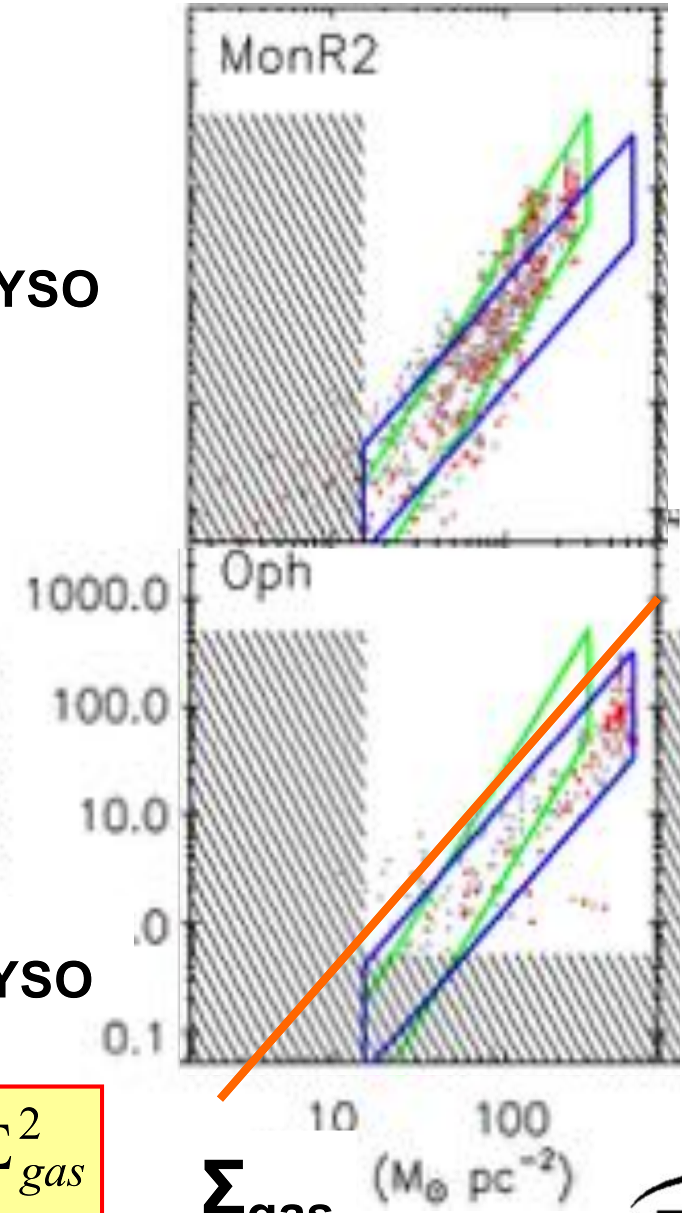
Sol. N. Molecular Clouds Show Quadratic SF Relations

Fig. 1, Gutermuth+ (2011)

MonR2 cloud of Solar Neighbourhood



Σ_{YSO}



Σ_{YSO}

Σ_{gas}

Fig. 9, Gutermuth+ (2011)

$$\Sigma_{YSO} \propto \Sigma_{gas}^2$$

Sol. N. Molecular Clouds Show Quadratic SF Relations

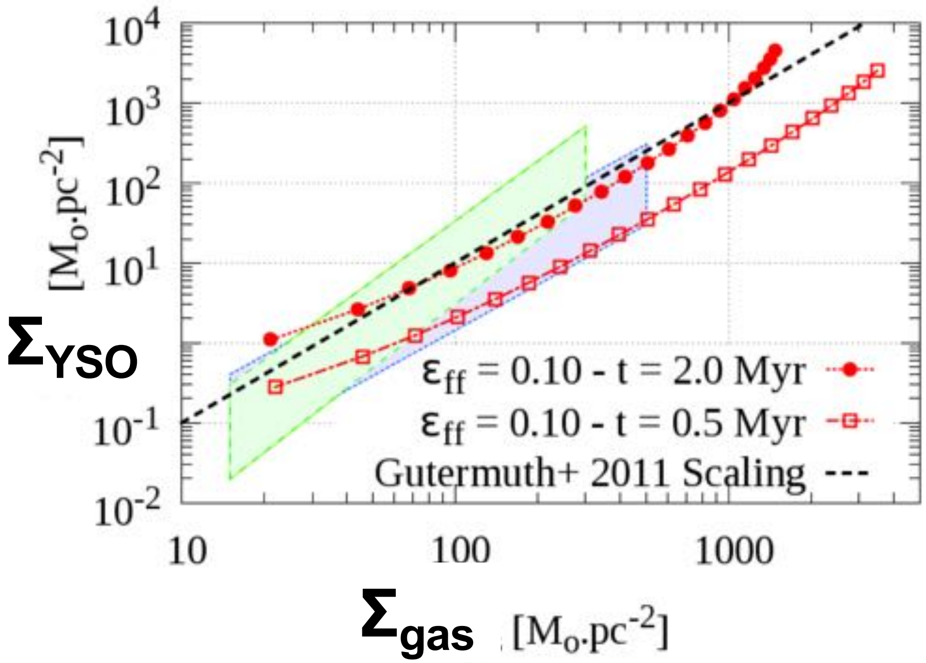


Fig 3, Parmentier & Pfalzner (2013)

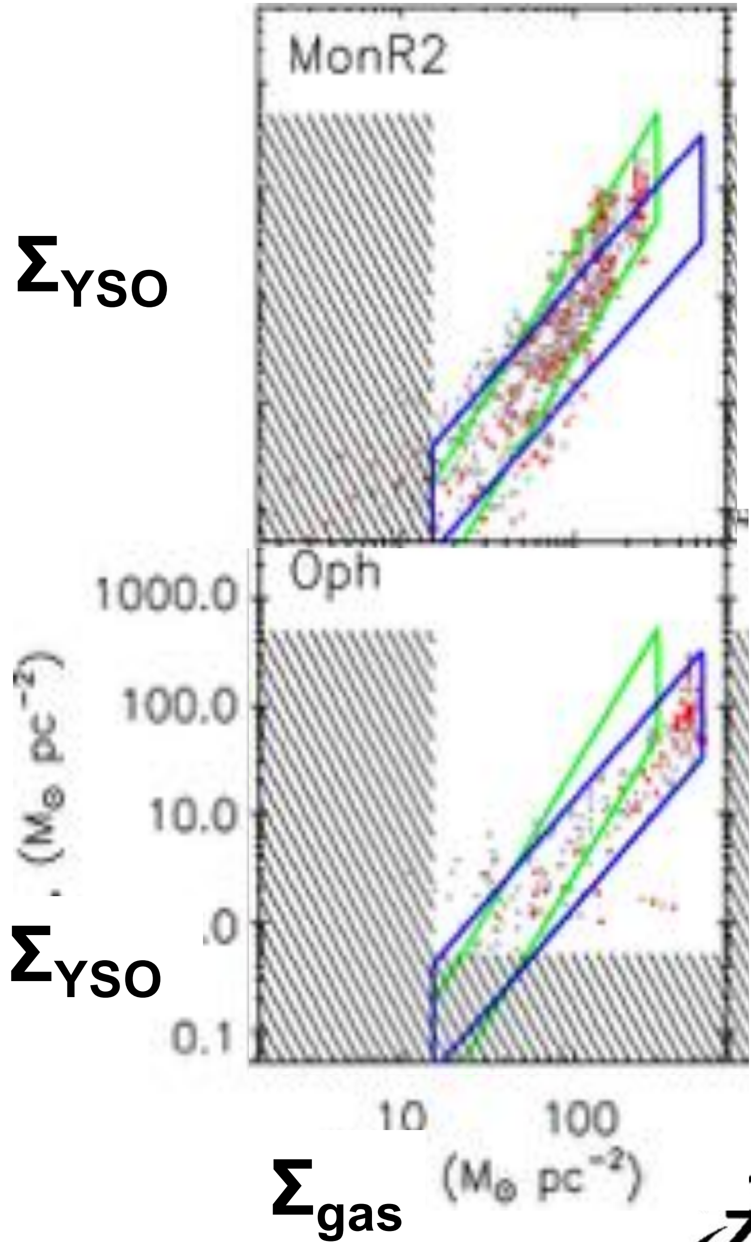
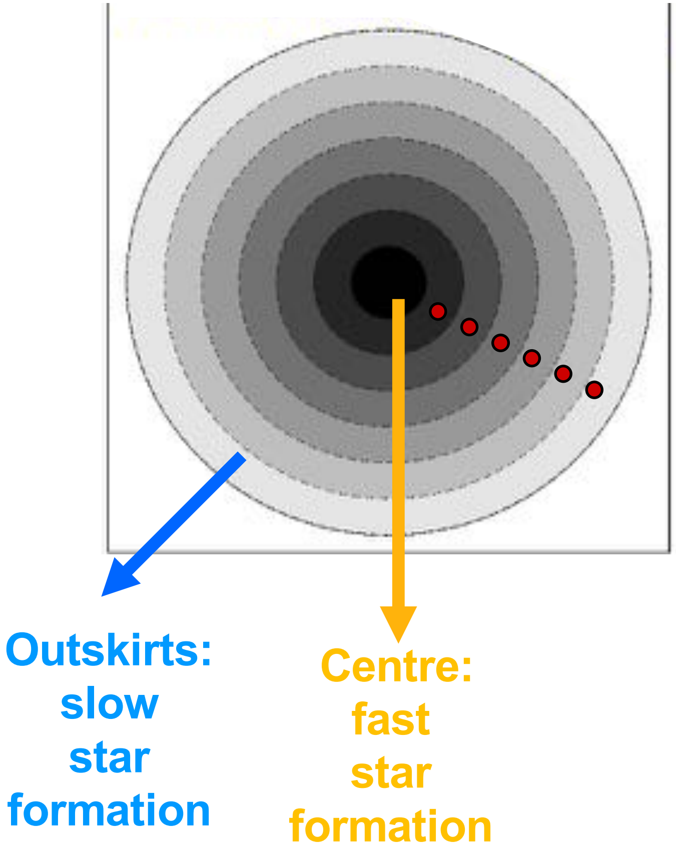


Fig. 9, Gutermuth+ (2011)

From a Local SF Relation …

Local perspective:
- **Contour-by-contour basis**
- **One clump is enough**

Clump distance: e.g. 500 pc



… to a Global (= Third) SF Relation

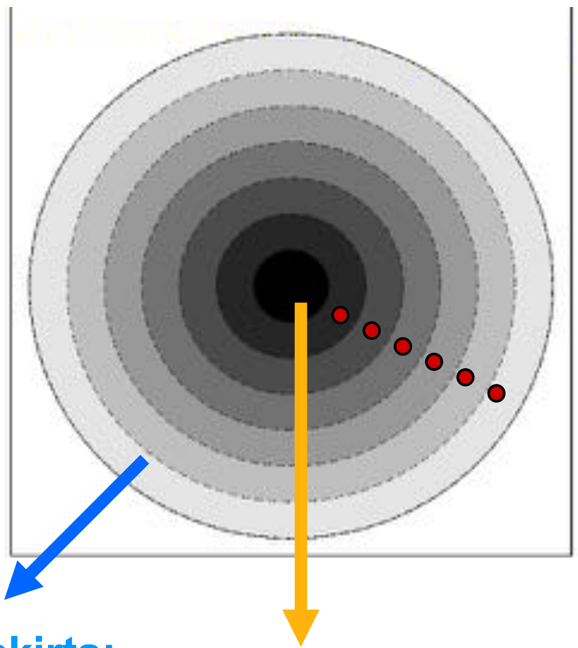
Clump at a distance where it cannot be resolved

$(\Sigma_{gas}^{glob}, \Sigma_{SFR}^{glob})$

Local perspective:

- **Contour-by-contour basis**
- **One clump is enough**

Clump distance: e.g. 500 pc

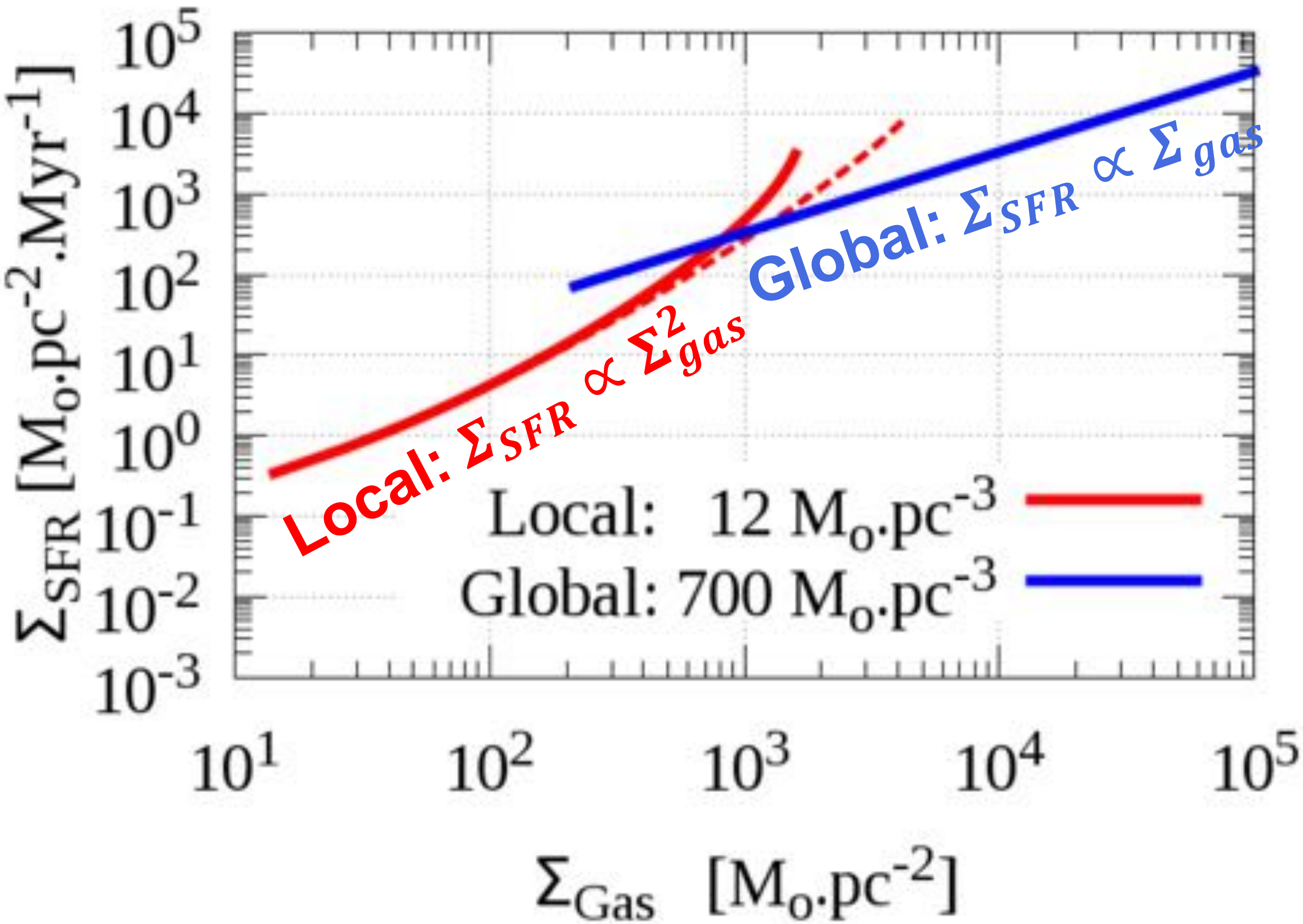


Global perspective:

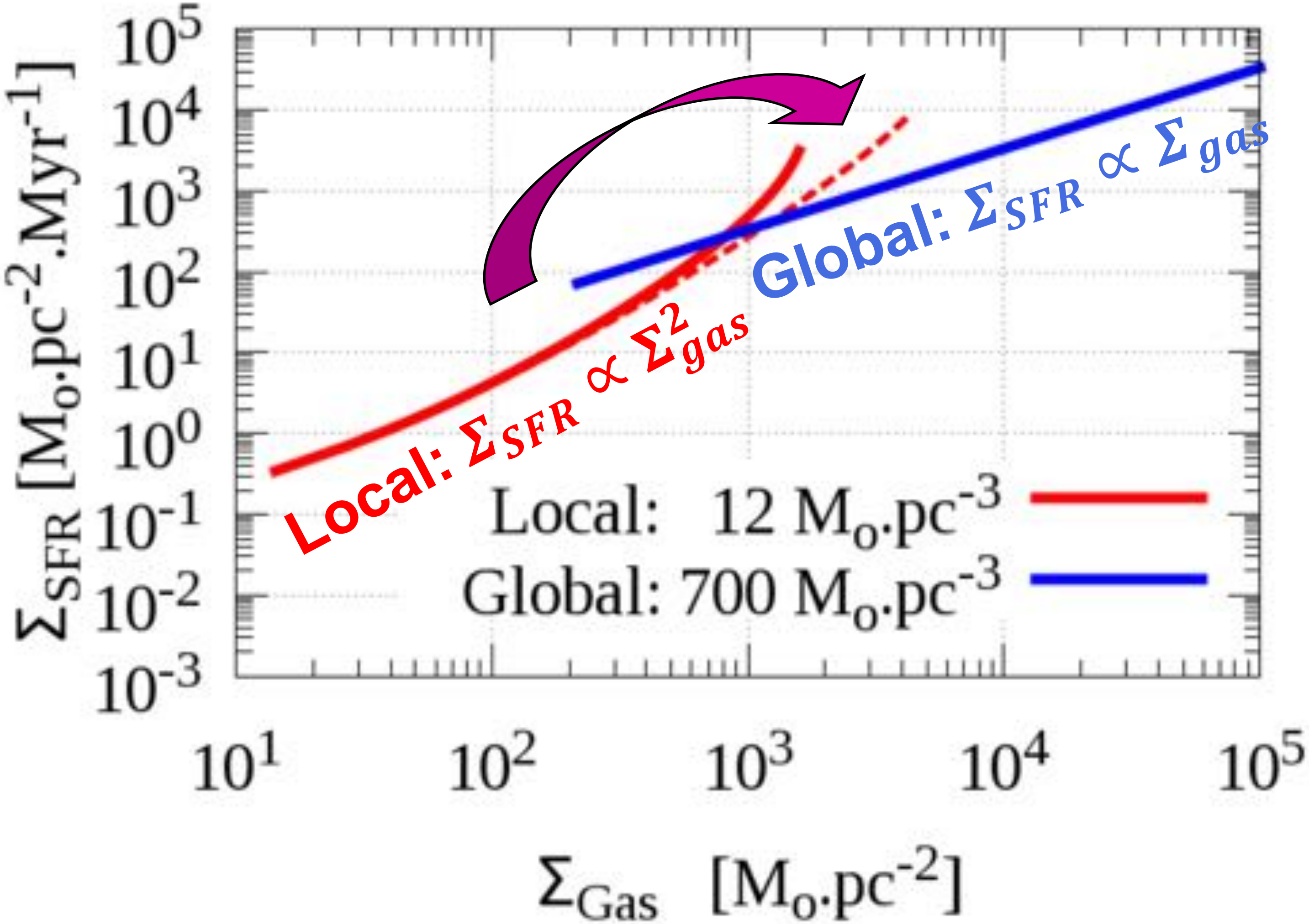
- **A population of clumps is needed**
- **e.g. HCN(1-0) molecular clumps**
- **To first order: common free-fall time**
  - **⟶ Slope: 1**
  - **⟶ Third / linear SF relation**

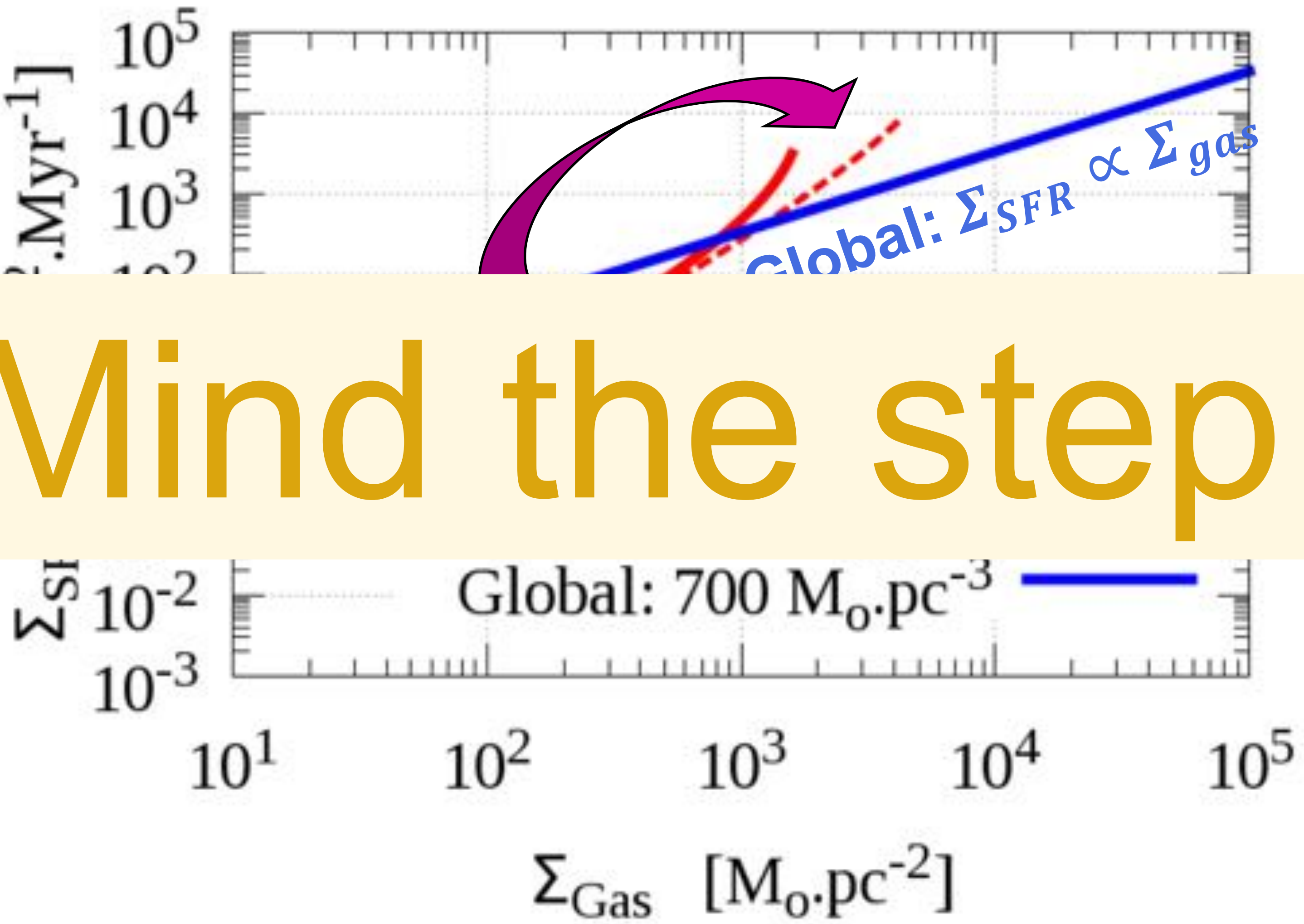
III. $\Sigma_{SFR} \propto \Sigma_{gas}$

Composite SF Relation: II + III



Break-Point in Composite SF Relation





Mind the step !

Break-Point in Composite SF Relation

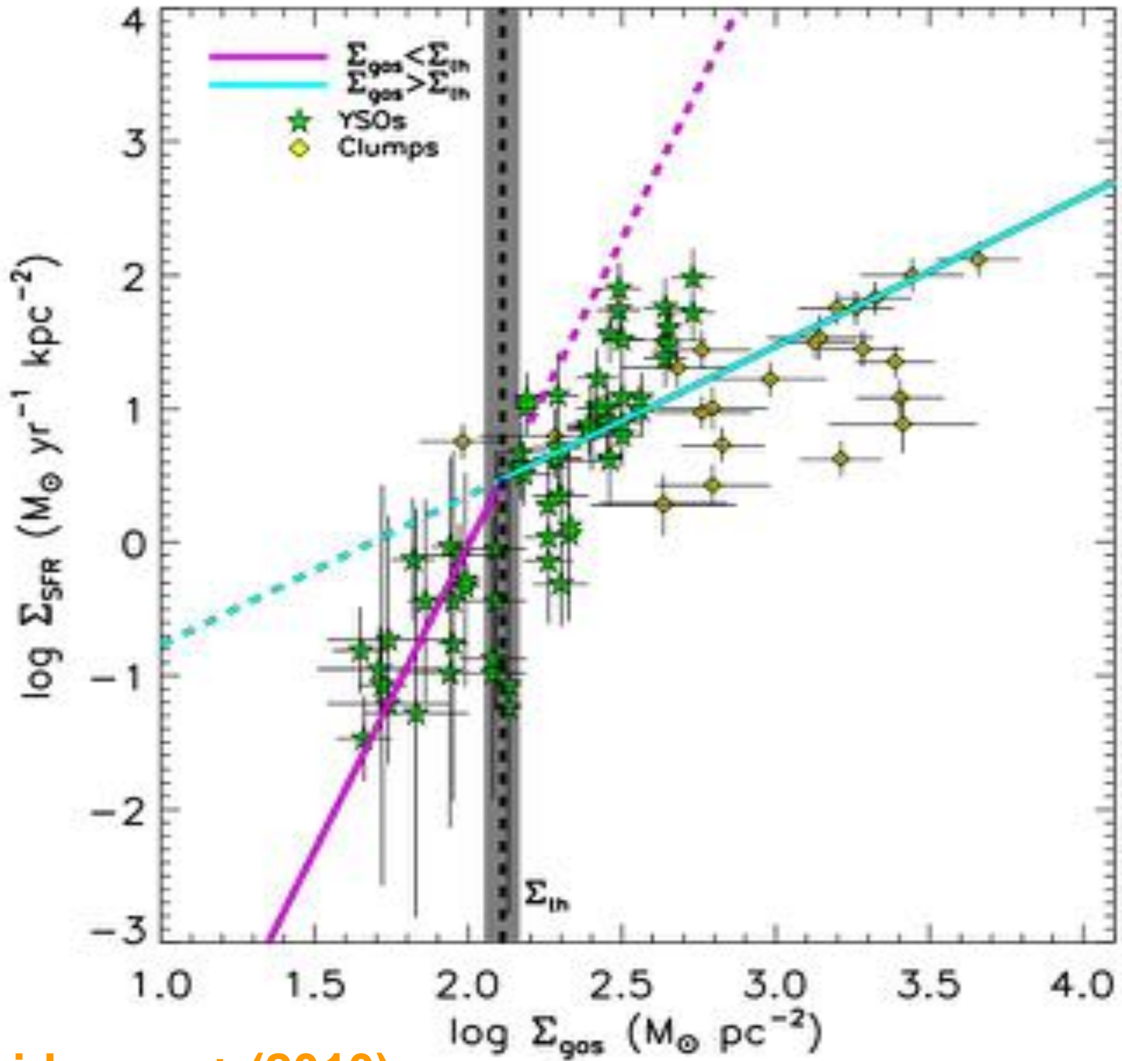


Fig. 10, Heiderman+ (2010)

Break-Point in Composite SF Relation

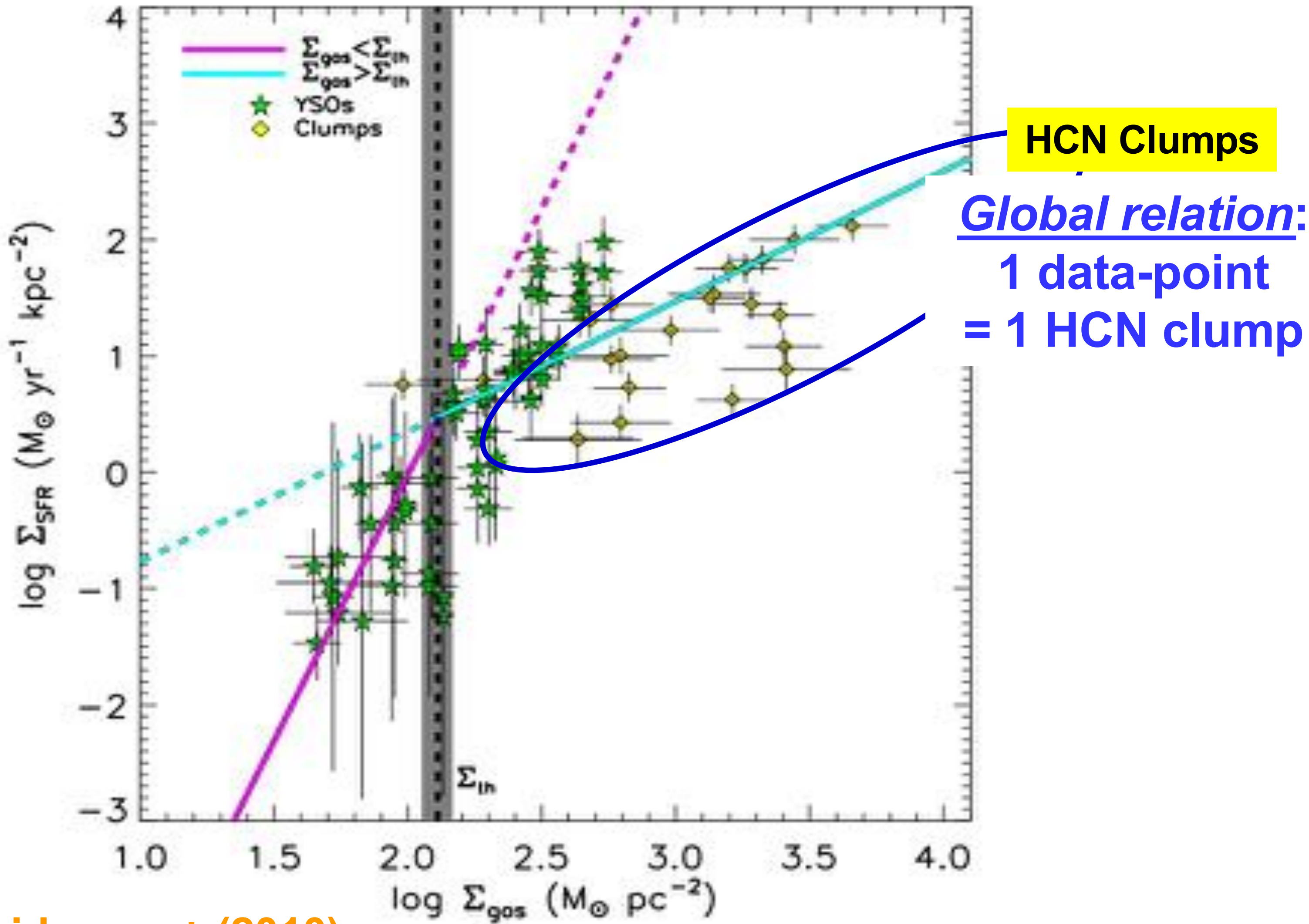
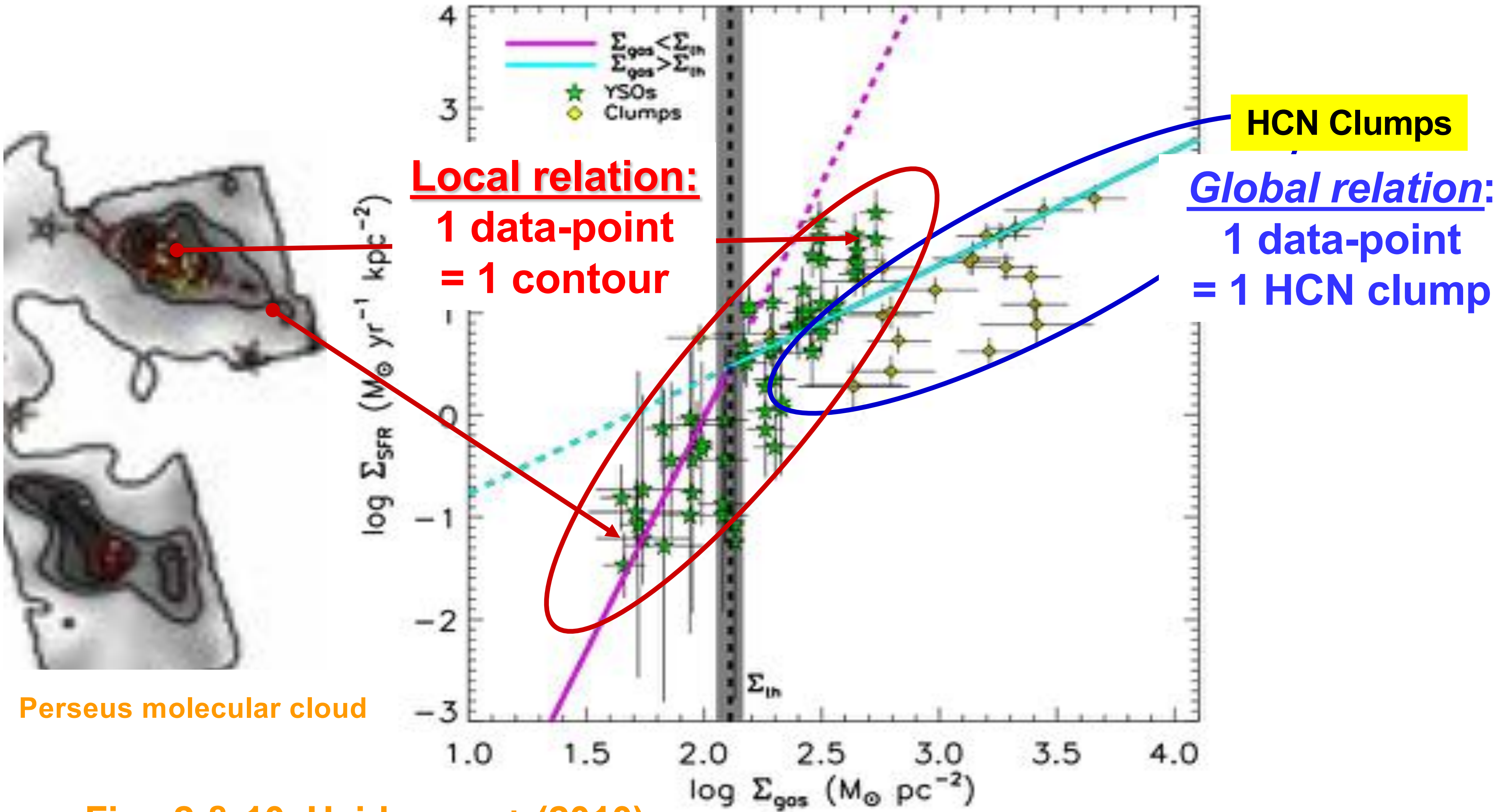


Fig. 10, Heiderman+ (2010)

Break-Point in Composite SF Relation

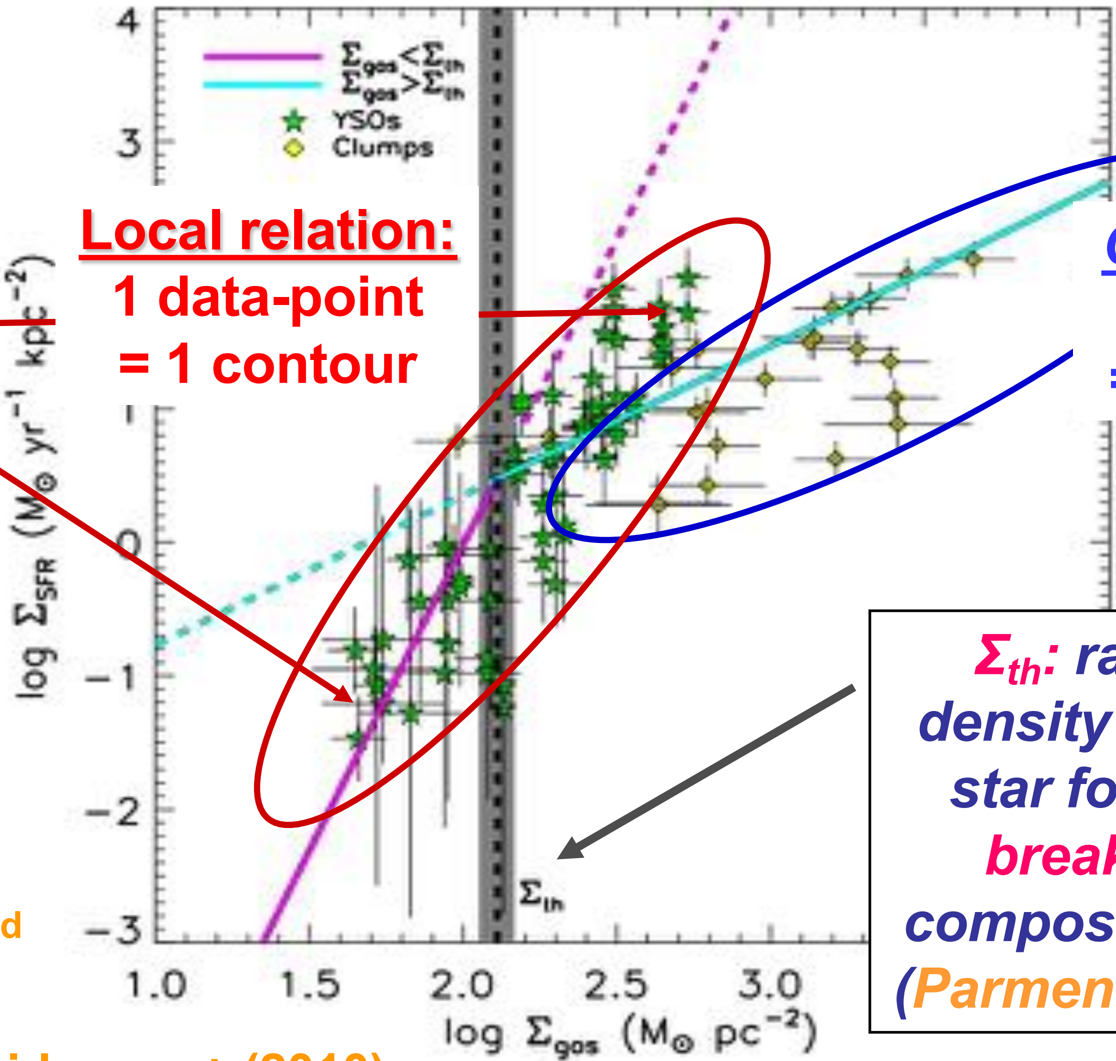


Perseus molecular cloud

Figs 2 & 10, Heiderman+ (2010)

Interpretation of Break-Point

Perseus molecular cloud



Local relation:
1 data-point
= 1 contour

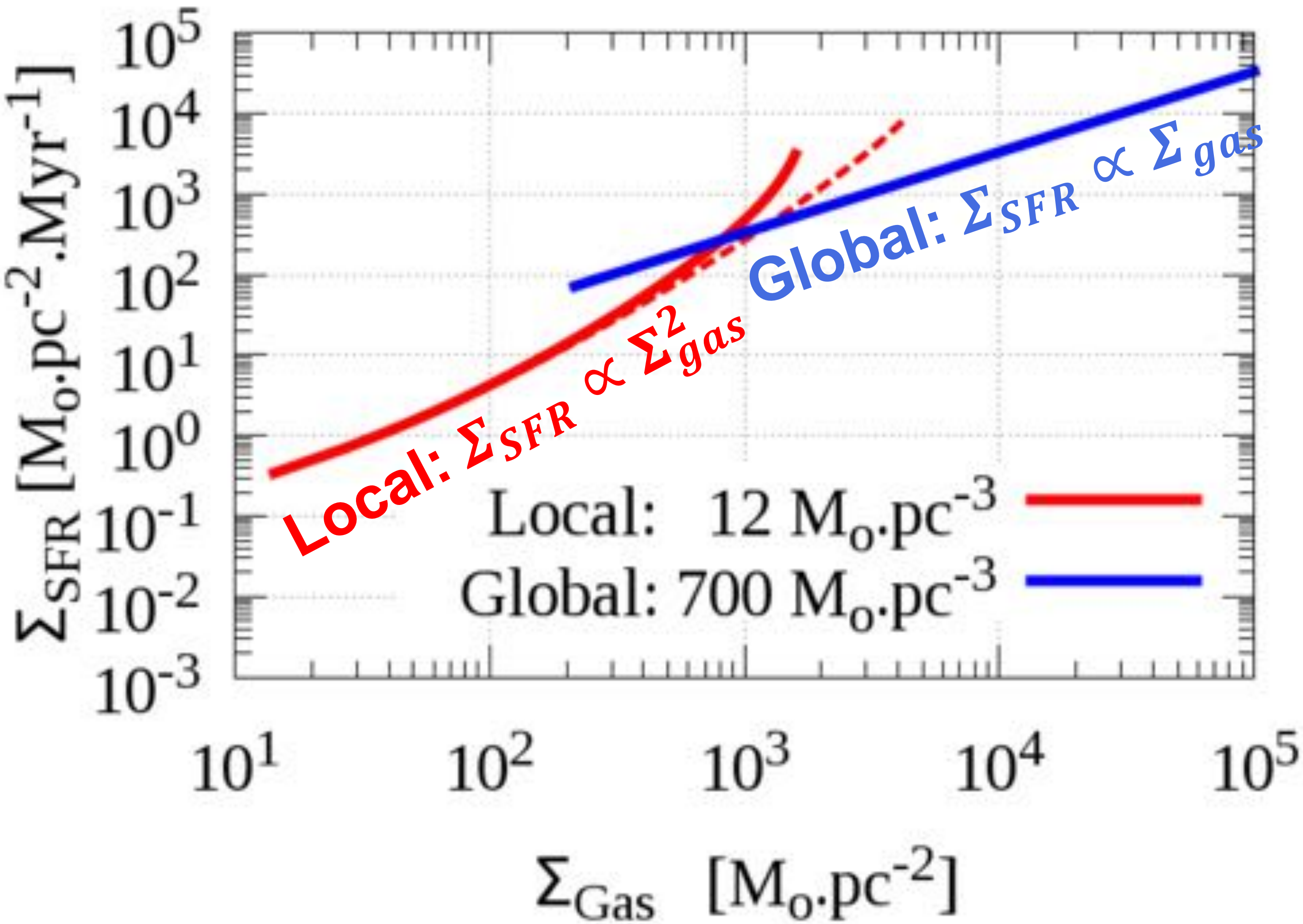
HCN Clumps

***Global relation*:**
1 data-point
= 1 HCN clump

Σ_{th}: rather than a density threshold for star formation, the break-point of a composite SF relation (Parmentier 2016, ApJ)

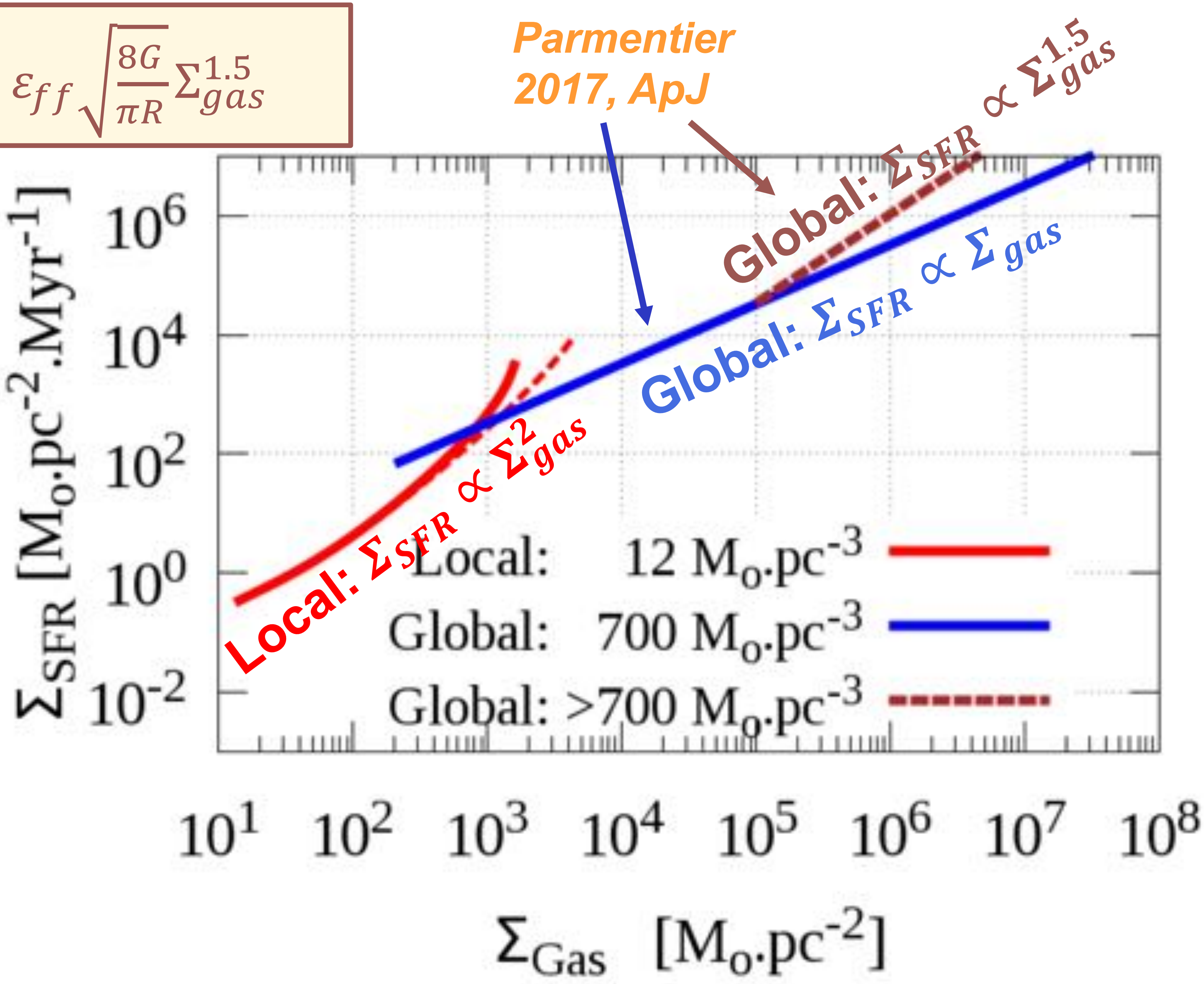
Figs 2 & 10, Heiderman+ (2010)

Composite SF Relation: II + III

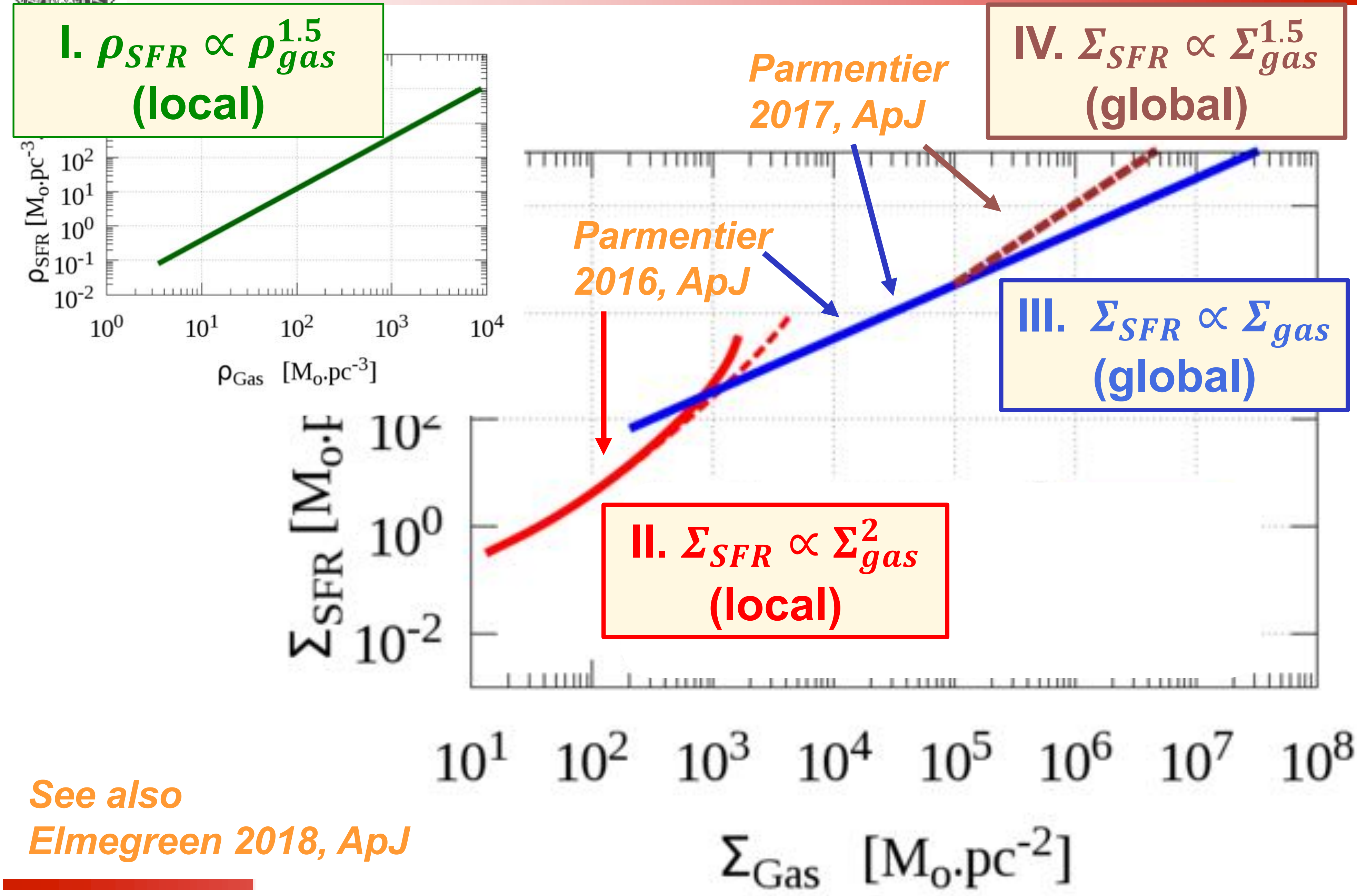


Fourth SF Relation (the very dense gas)

IV. $\Sigma_{SFR} = \varepsilon_{ff}\sqrt{\frac{8G}{\pi R}}\Sigma_{gas}^{1.5}$



4 Star Formation Relations for Molecular Clumps



See also
Elmegreen 2018, ApJ

Star Formation Relations and Co.

Shell – by – shell :

$$\rho_{SFR} \cong \varepsilon_{ff} \frac{\rho_{gas}}{\tau_{ff}} \propto \varepsilon_{ff} \frac{\rho_{gas}}{\left(\rho_{gas}\right)^{-1/2}} \propto \rho_{gas}^{3/2}$$

Contour – by – contour :

$$\Sigma_{SFR} \approx \Sigma_{gas}^{2}$$

Clump-by-clump (constant $\langle\rho_{gas}\rangle$):

$$\langle\Sigma_{SFR}\rangle \propto \langle\Sigma_{gas}\rangle^{1}$$

Clump-by-clump (increasing $\langle\rho_{gas}\rangle$):

$$\langle\Sigma_{SFR}\rangle \propto \langle\Sigma_{gas}\rangle^{3/2}$$

Star Formation Relations and Co.

Shell – by – shell :

$$\rho_{SFR} \cong \varepsilon_{ff} \frac{\rho_{gas}}{\tau_{ff}} \propto \varepsilon_{ff} \frac{\rho_{gas}}{\left(\rho_{gas}\right)^{-1/2}} \propto \rho_{gas}^{3/2}$$

Contour – by – contour :

$$\Sigma_{SFR} \approx \Sigma_{gas}^{2}$$

Clump-by-clump (constant $\langle\rho_{gas}\rangle$):

$$\langle\Sigma_{SFR}\rangle \propto \langle\Sigma_{gas}\rangle^{1}$$

Clump-by-clump (increasing $\langle\rho_{gas}\rangle$):

$$\langle\Sigma_{SFR}\rangle \propto \langle\Sigma_{gas}\rangle^{3/2}$$

- **Constant ε_{ff}: the slope is not necessarily 1.5**
- **Slope ≠ 1.5 does not necessarily discard a scenario in which star formation proceeds with a constant ε_{ff}**

Star Cluster Evolution after Gas Expulsion

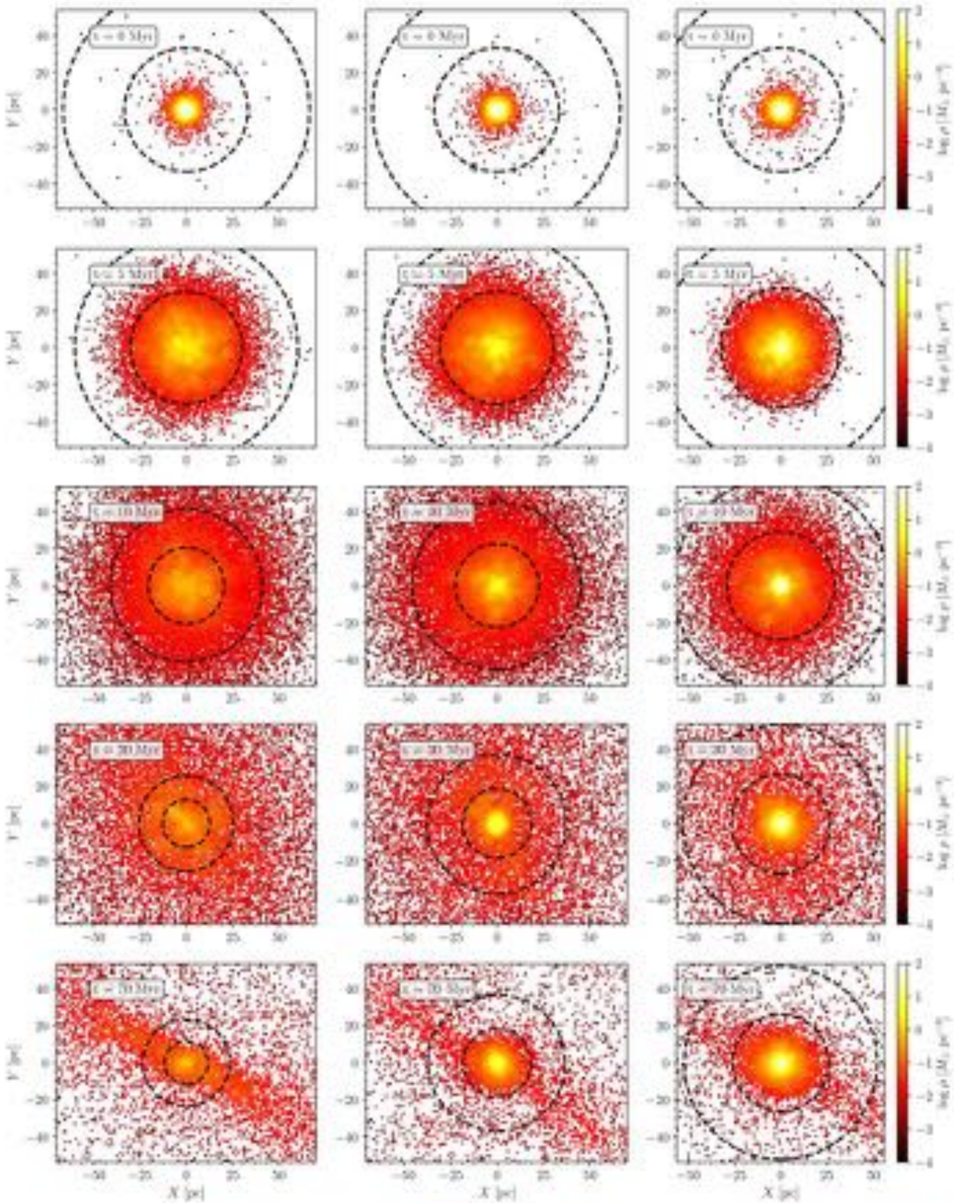
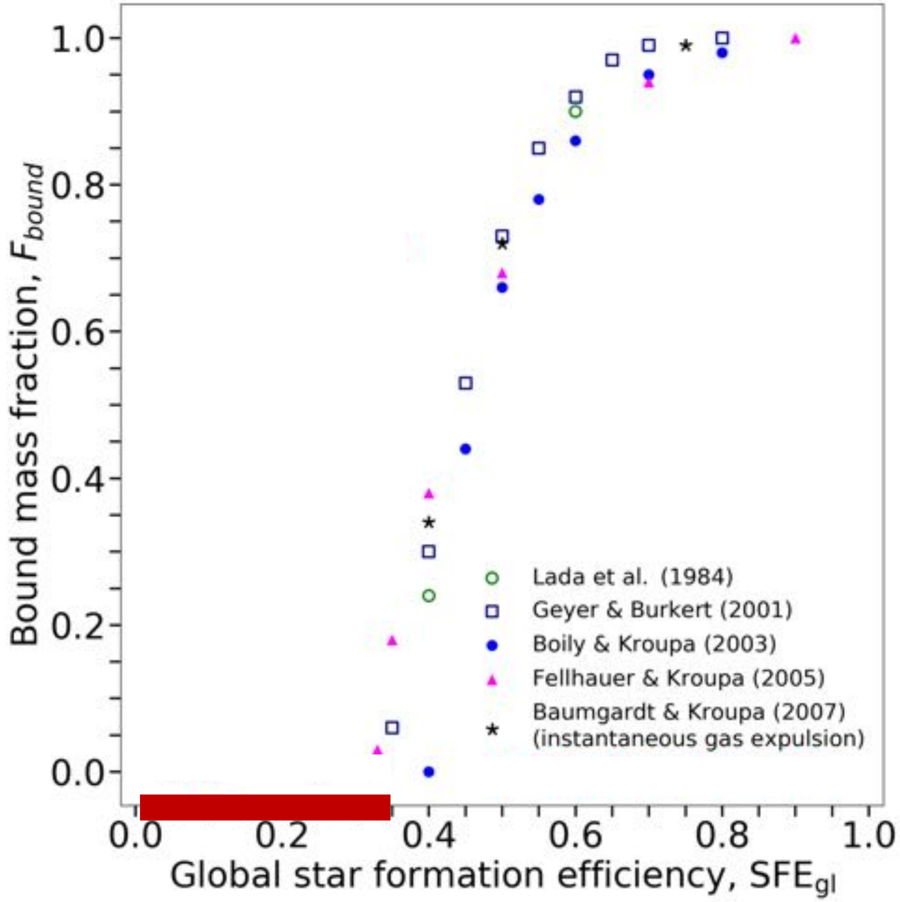


Fig 1, Shukirgaliyev, Parmentier, Just & Berczik (2018)

Short-Term Evolution

Instantaneous gas expulsion



- **A decade ago: star clusters formed with an SFE less than 1/3 do not survive (aka cluster infant mortality)**

Back to the Second (Local) SF Relation

$\Sigma_{YSO} \propto \Sigma_{gas}^2$ → $\Sigma_{gas} \propto \frac{\Sigma_{YSO}}{\Sigma_{gas}} \propto \varepsilon_{2D}$

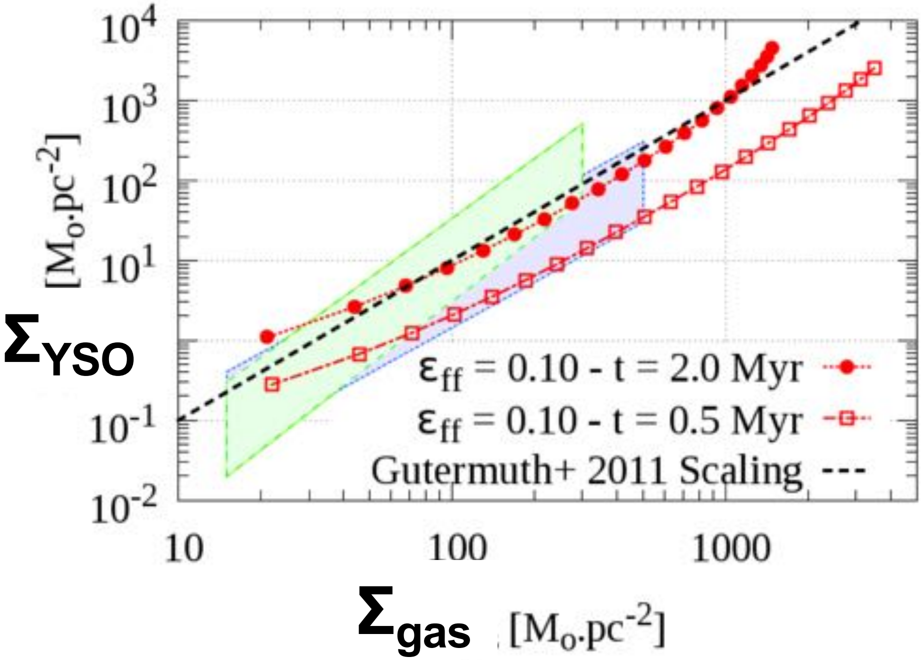


Fig 3, Parmentier & Pfalzner (2013)

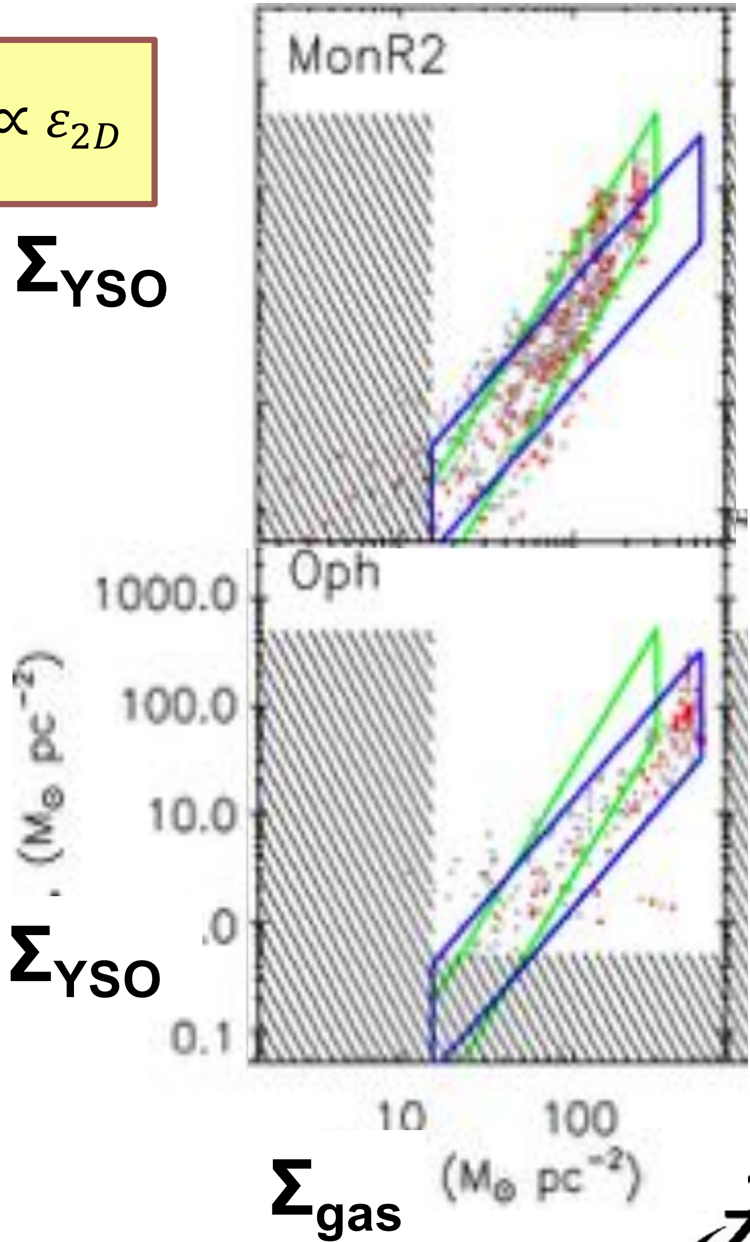
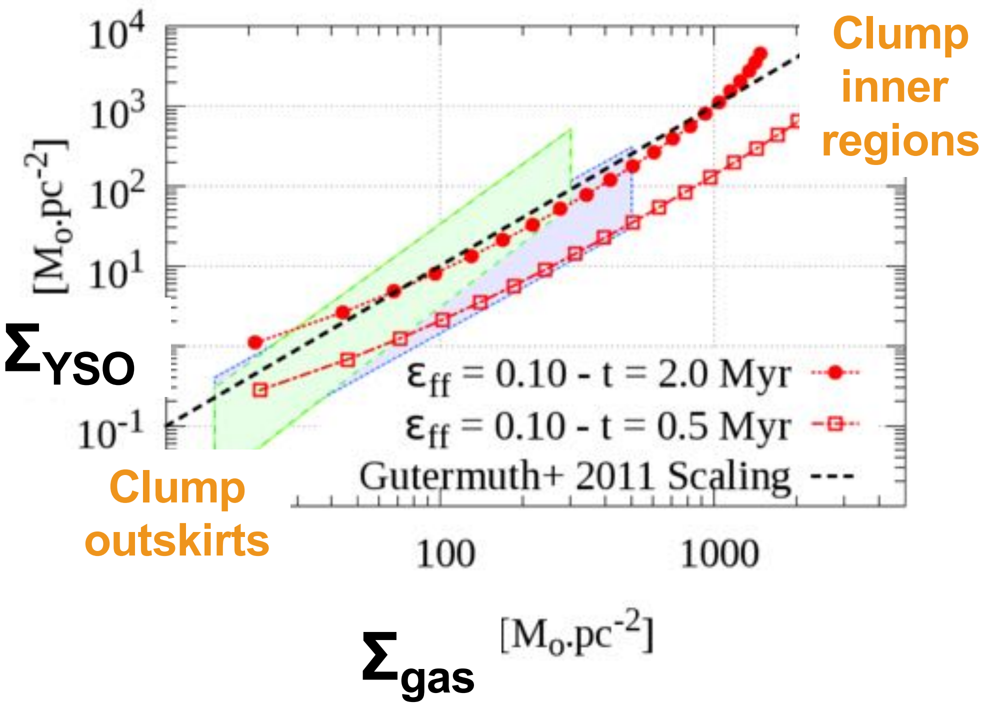
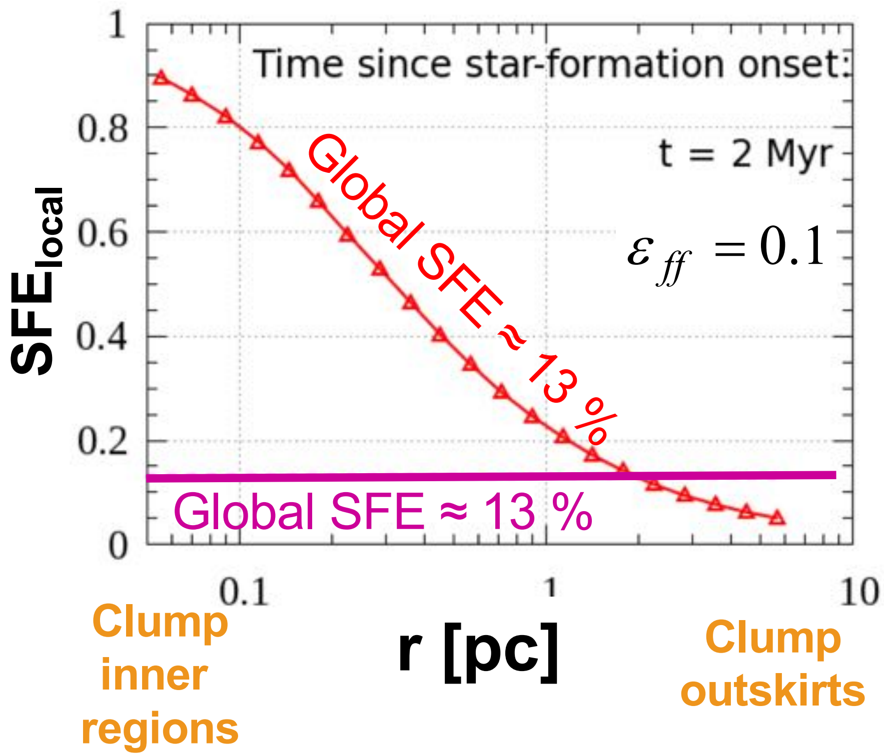


Fig. 9, Gutermuth+ (2011)

SFE Radial Variations





<u>Local Star Formation Relation:</u>

Superlinear / Quadratic

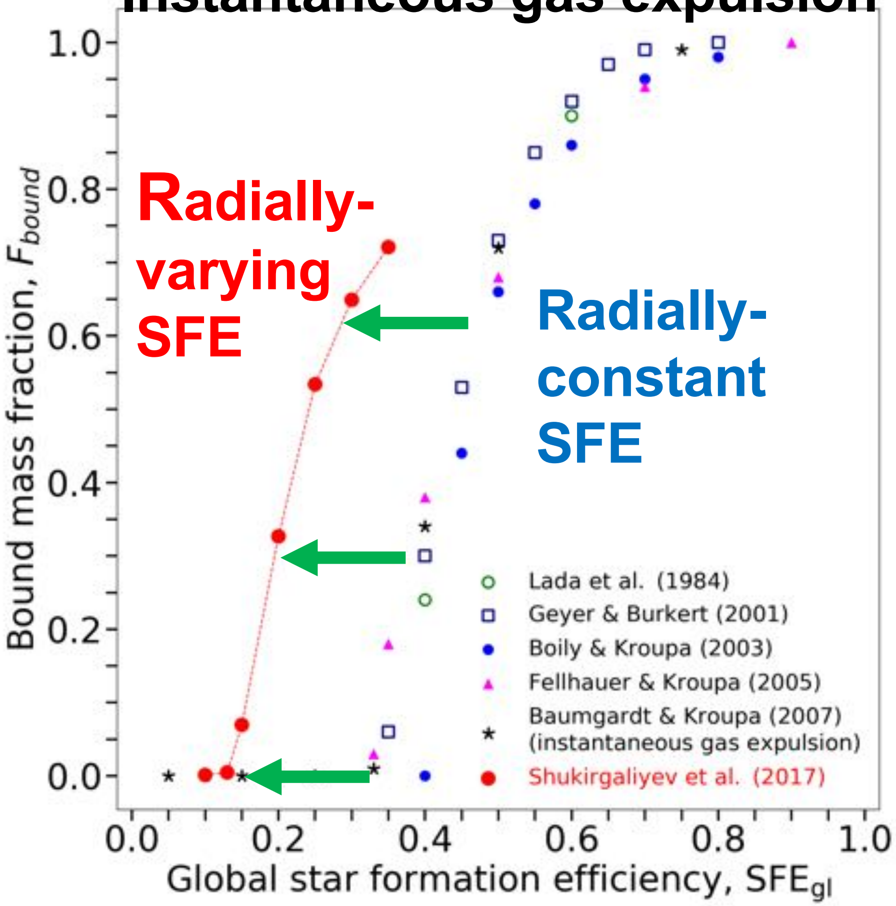
<u>Local star formation efficiency :</u>

SFE_{local}(inner) > SFE_{local}(outer)

Figs 3 and 10, Parmentier & Pfalzner (2013)

Violent Relaxation

Instantaneous gas expulsion

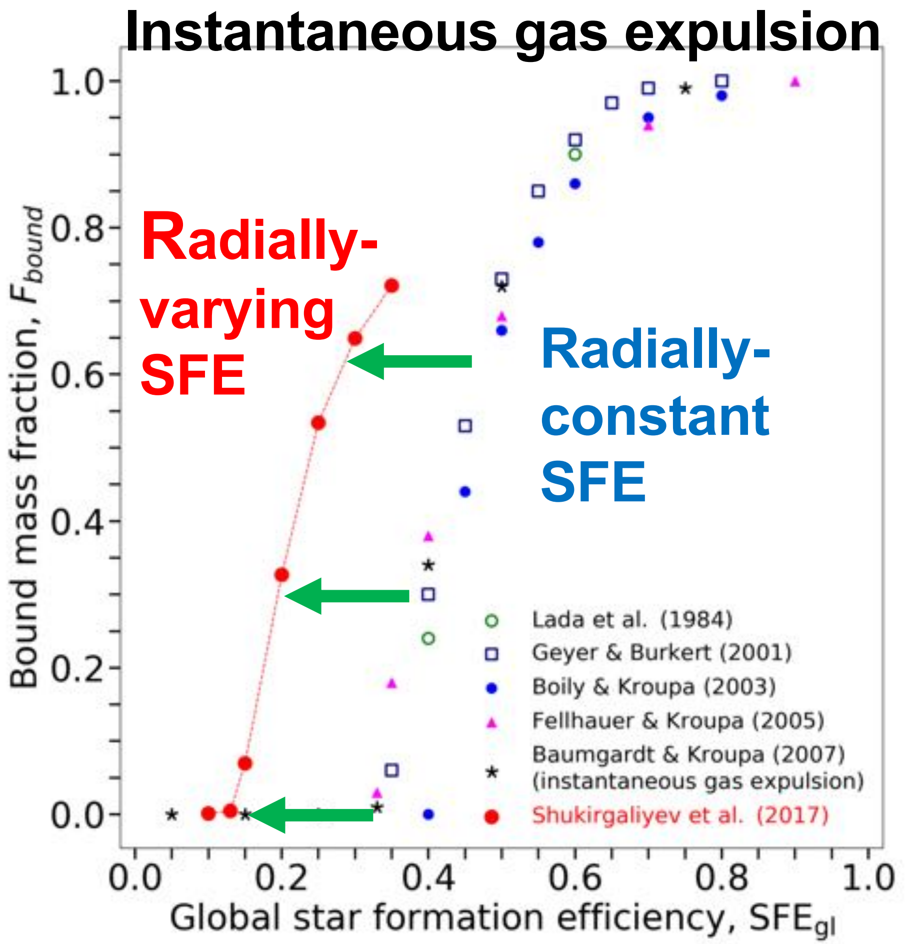


Based on Fig8 in Shukirgaliyev, Parmentier, Berczik & Just (2017)

- Clusters reaching a global SFE higher than 13% do survive

- Strongly reduced infant mortality
  - Despite solar-neighbourhood tidal field inclusion!
  - One model cluster with a global SFE of 25% and a birth mass of 15E3M_{sun} has a dissolution time of 2.9Gyr !

Longer-Term Evolution



Based on Fig8 in Shukirgaliyev, Parmentier, Berczik & Just (2017)

- Cluster <u>Teenage</u> Mortality
  - One model cluster with a global SFE of 25% and a birth mass of 15E3M_{sun} has a dissolution time of 2.9Gyr !
  - Most clusters formed with a global SFE of 15% die within a Gyr

Long-Term Evolution of the SFE≥15% Clusters

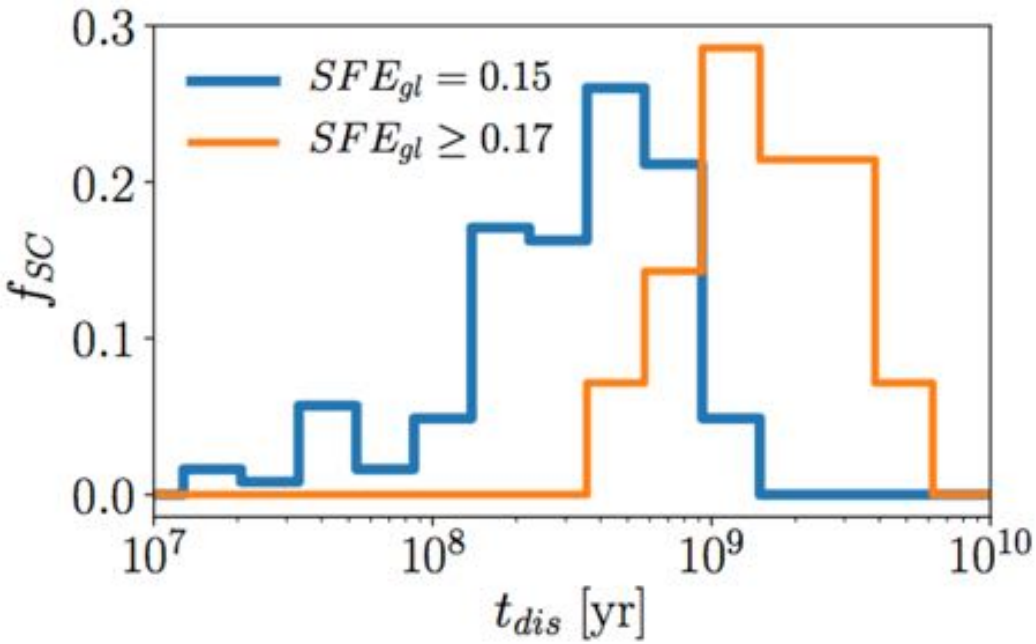


Fig 7, Shukirgaliyev, Parmentier, Just & Berczik (2018)

- Most clusters formed with a global SFE of 15% die within a Gyr
- Cluster teenage mortality
- Most clusters formed with a global SFE of at least 17% have a life-expectancy longer than 1Gyr: a higher SFE generates a more compact structure by the end of violent-relaxation

Take-Away Messages

- The slopes of star formation relations measured for molecular clumps depend on:
  - what is measured,
  - how it is measured,
  - on top of SF physics

- When interpreting star formation relations, first thought should be "pitfalls ahead"

- Cluster infant mortality

  → Cluster teenage mortality